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A Low-Cost Beam Profiler Based On Cerium-Doped Silica Fibers

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Abstract

A beam profiler called the Universal Beam Monitor (UniBEaM) has been developed by D-Pace Inc. (Canada) and the Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, University of Bern (Switzerland). The device is based on passing 100 to 600 micron cerium-doped optical fibers through a particle beam. Visible scintillation light from the sensor fibers is transmitted over distances of tens of meters to the light sensors with minimal signal loss and no susceptibility to electromagnetic fields. The probe has an insertion length of only 70mm. The software plots the beam intensity distribution in the horizontal and vertical planes, and calculates the beam location and integrated profile area, which correlates well with total beam current. UniBEaM has a large dynamic range, operating with beam currents of ~pA to mA, and a large range of particle kinetic energies of ~keV to GeV, depending on the absorbed power density. Test data are presented for H^- beams at 25keV for 500µA, and H^+ beams at 18MeV for 50pA to 10µA. Maximum absorbed power density of the optical fiber before thermal damage is discussed in relation to dE/dx energy deposition as a function of particle type and kinetic energy. UniBEaM is well suited for a wide variety of beamlines including discovery science applications, radio-pharmaceutical production, hadron therapy, industrial ion beam applications including ion implantation, industrial electron beams, and ion source testing.

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1. Introduction

For beamline operators, beam profilers are crucial for verifying beam size and position, as well as the beam intensity distribution shape. Beam profilers allow operators to observe the effects of focusing and steering in real time, and to observe the real-life effects of vacuum quality, space charge and second-order effects causing beam halo. However, the use of beam profilers with industrial accelerator beamlines is often limited or non-existent despite the advantages they provide, often because of budget and space limitations, as noted by Dehnel et al. (2013).

A beam profiler based on doped SiO_2 optical fibers was designed and tested at the Albert Einstein Center for Fundamental Physics (AEC), Laboratory for High Energy Physics (LHEP), University of Bern, Switzerland. This beam profiler, called the Universal Beam Monitor (UniBEaM™), was conceived to meet the requirements for a simple, robust, compact, inexpensive and continuous-monitoring beam profiler. UniBEaM has a large dynamic range, operating with beam currents of ~pA to mA, and a large range of particle kinetic energies of ~keV to GeV, depending on the absorbed power density. Braccini et al. (2012), and Auger et al. (2016) described the use of UniBEaM on their 2MeV and 18MeV proton accelerators. UniBEaM was licensed and commercialized by D-Pace Inc. Canada. This paper describes the commercial UniBEaM design and provides example measurements.

2. UniBEaM System Description

UniBEaM is an alternative to conventional wire scanners. Unlike available commercial wire scanners in the same price range, UniBEaM is superior for measuring a wide range of beam currents and particle kinetic energies, and is particularly well suited to measuring low beam currents. The UniBEaM signal is optical rather than electrical, making small signals insusceptible to interference. UniBEaM also provides control of the speed and position of the fiber, so that the user has flexibility to control integration time for low current beams and to synchronize fiber positioning with pulsed beams. Rotating helical wire scanners do not allow this. Dual orthogonal fibers also occupy less space along the beam axis than rotating helical wire scanners.

Each UniBEaM probe has two sensing fibers; one for X-profiles and one for Y-profiles (see Fig. 1 & Fig. 2). The sensor fibers are moved through the beam by stepper motor actuators. Home switches ensure accurate fiber positioning. There are no electronic components in the probe, making the probe radiation resistant. Two ports in each probe provide access to replace the fibers. Replacement sensor fibers are provided in protective cartridges which also serve as the installation tools. Fiber replacement takes about two minutes following vacuum venting. UniBEaM is an in-line device – it does not require a separate vacuum box or beam-pipe cross. KF and CF flanges options are available. With KF bulkhead clamps, the device has an insertion length of only 70mm.

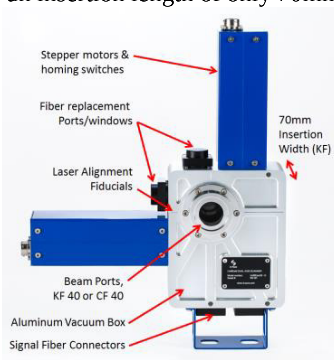

Fig. 1. D-Pace’s commercial UniBEaM dual axis probe

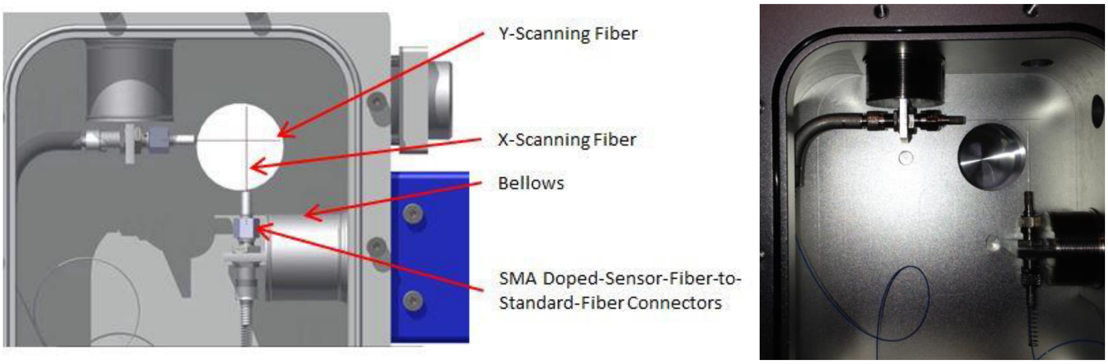

Fig. 2. Internal views of UniBEaM showing the X & Y scintillating sensor fibers and fiber connector

The optical sensing fibers were made by the University of Milano-Bicocca's Department of Materials Science (UMB-DMS) using the sol-gel process. The fibers are SiO_2 doped with Ce^{3+} ions as luminescent activators, and are drawn to a diameter of 200µm. UMB-DMS developed the fiber for dosimetry. The fiber produces intense and fast radio luminescence (RL) emitted by the Ce^{3+} dopant ions, with an emission band centered at 450nm, as stated by Vedda et al. (2004), and Mones et al. (2006). The SiO_2 fiber also produces luminescence due to Cherenkov radiation, which is characterized by a broad spectral emission in the blue-UV wavelength region.

The sensor fibers are coupled to 200µm core, hard-clad, 0.5 NA fibers within the probe using SMA in-vacuum connectors. These non-scintillating, in-vacuum fibers pass through vacuum feedthroughs and are terminated on the atmosphere side of the probe with a second pair of optical SMA connectors. Another pair of optical fibers is used to connect the probe to the UniBEaM controller. These fiber-optic patch cables are 400µm, 0.5 NA fibers, which transmit the optical signal, with very low signal loss, to a silicon photo multiplier (SPM) located in the UniBEaM controller. The scintillation light can be transmitted tens or even hundreds of meters with minimal signal loss, and with no susceptibility to electromagnetic fields.

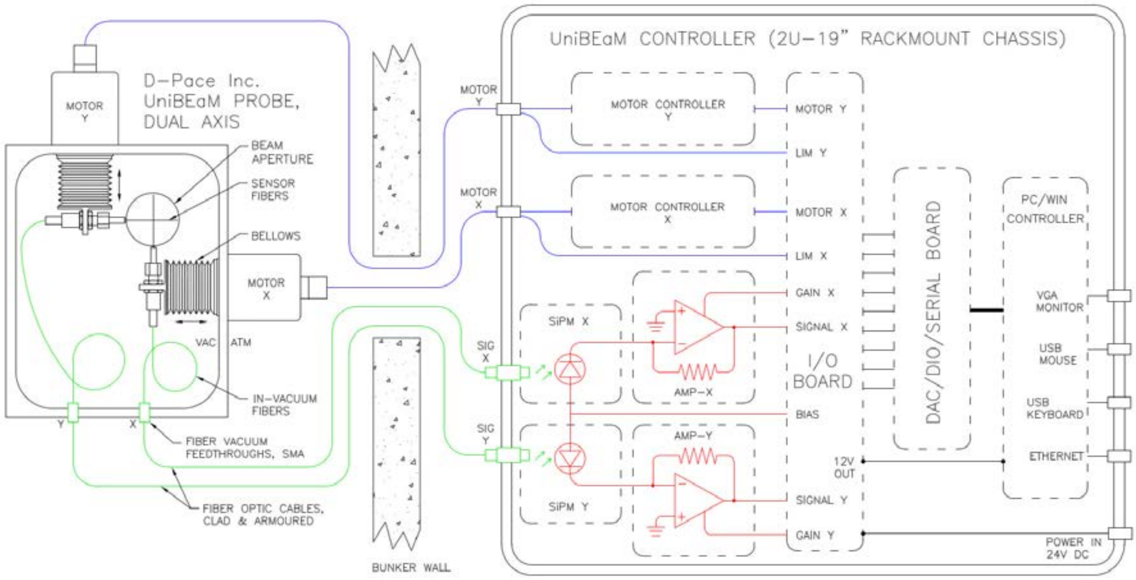

Fig. 3. UniBEaM commercial system architecture

The SPM sensors are very sensitive, fast, compact, and robust solid-state light sensors. The SPM sensor's spectral sensitivity is well matched to the spectral emission of the cerium-doped fiber. The SPMs utilize approximately 5000 sensor channels. Each channel acts as an independent avalanche photo diode, and behaves as a photo-activated switch, but the integrated total current of the large number of SPM channels results in a quasi-analog signal. The SPM bias voltage was optimized to achieve high gain while minimizing dark current to acceptable levels. The SPM active area was chosen based on compromises between sensitivity, resolution, response time and dark current.

Transimpedance amplifiers (2MHz, -3dB) with four orders of magnitude of programmable gain are used to convert the SPM photocurrent to voltage signals suitable for analog-to-digital conversion (ADC) (±10V, 14bit, 20kS/s). A dedicated amplifier for each axis allows simultaneous X & Y profile scanning. At the fiber speed of 10mm/second, and position increments of 200µm, 5 samples per position increment per channel are averaged. An integrated single-board PC is used for signal processing and the graphical user interface. UniBEaM can be operated as a standalone system with the addition of a mouse and keyboard, or controlled using Ethernet and text-based commands.

Fig. 4. Ce^{3+} doped SiO_2 fiber (L) and a replacement fiber cartridge (R)

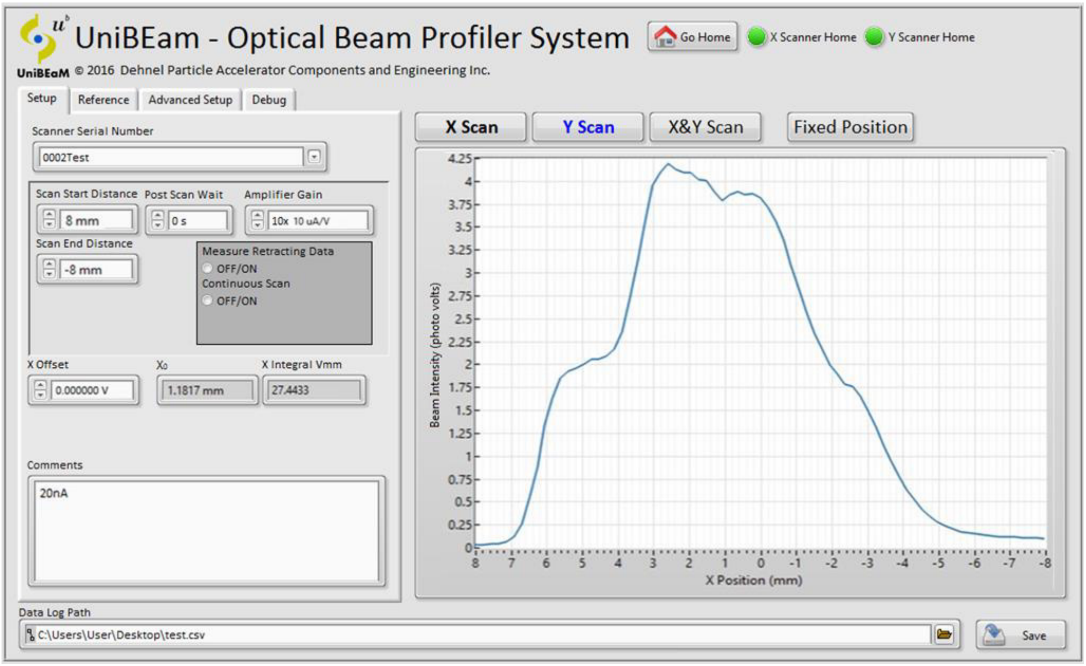

Fig. 5: UniBEaM software user interface, showing intensity profile for an 18MeV 20nA proton beam

The UniBEaM software acquires and analyzes beam profiles (see Fig. 5). The user can change the position step size, and the scan-start and scan-end positions. Single or continuous scans can be acquired. The profile plot of each pass of the fiber can be displayed separately, or overlaid in persistent-display mode to establish time-domain trends. The fiber scanning speed is adjustable. Slower scan speeds enable greater signal averaging for improving the signal-to-noise ratio of low beam current scans. The software calculates the beam centroid and the integral of the intensity profile. The user can set the zero value for the position and integral calculations. Profiles are saved in a CSV-format file with header data.

The UniBEaM software has a second operation mode, which allows the fiber to be moved to a fixed location, and the beam intensity at this position is measured as a function of time, displayed as a strip chart.

3. Maximum Absorbed Power Density of Silica Fiber

18MeV proton beams with currents of 20μA and a beam diameter of 5mm caused a temporary reduction of the linear response due to thermal effects on the SiO_2 fibers. For the 20uA beam the responsivity decreased by 25% following a 3 second pass of the fiber through the beam. This is an average <u>beam</u> power density of 18 W·mm^{-2}. At 18MeV, the dE/dx for SiO_2 is 5.44 MeV/mm (SRIM software version 2013.00). A 200μm fiber has an average thickness of 0.157 mm, so the energy lost by the protons in the fiber is 0.85MeV, and the average <u>absorbed</u> power density (P_D) of the fiber was calculated (equation 1) to be 0.9 W·mm^{-2}. We considered this the maximum absorbed power density of the fiber.

$$P_{D_{(Absorbed)}} = \frac{5.44\,\frac{MeV}{mm} \cdot 20\ \mu A \cdot 0.157\ mm}{\frac{\pi}{4}\,(5.0\ mm)^2} = 0.9\ W \cdot mm^{-2} \tag{1}$$

A calculation based on radiative heat transfer of an SiO_2 fiber, with an emissivity of $\epsilon = 0.88$ and a maximum temperature based on its glass transition temperature of $T_g = 1473$K, and a 100% view factor to a 300K blackbody, resulted in a calculated maximum beam power density of 0.74 W·mm^{-2}, which corresponds well with the maximum absorbed power density calculated above (equation 1). These P_D values for the SiO_2 compare favorably with the maximum DC power densities reported in the literature by Strehl (1995), (2006), for metal wire scanners (W-Re wire at P_D = 0.5 - 1 W·mm^{-2}).

4. Example UniBEaM Intensity Profiles

Auger et al. (2016), measured DC beams from their 18MeV IBA Cyclone cyclotron with their prototype UniBEaM, at currents as low as 1pA. For very low current measurements, they utilized a 200μm Ce^{3+} doped fiber in conjunction with silicon photon multipliers and a single-photon-counting apparatus to achieve a signal-to-noise ratio (SNR) of 10 at 18MeV 1pA. Beam currents were measured using a Faraday cup (see Fig. 6).

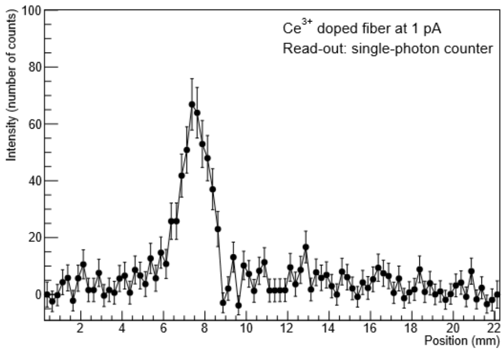

Fig. 6. Profile of an 18MeV 1pA H+ beam using photon counting method (courtesy of AEC-LHEP)

D-Pace used the commercial UniBEaM system described above on the same 18MeV cyclotron at H^+ currents of 12pA, 62pA, 100pA, 225pA, 1nA, and 400nA (see Fig. 7). Integrals of the profiles were plotted (see Fig. 8) versus the beam current measured with the Faraday cup. Even though the beams are not perfectly axisymmetric, there is still good linearity between a Faraday cup current and the beam intensity integral. AEC-LHEP reported similar findings with their prototype UniBEaM System. AEC-LHEP also reported that the linear response of the sensing fiber was lost at currents exceeding a few µA due to thermal effects.

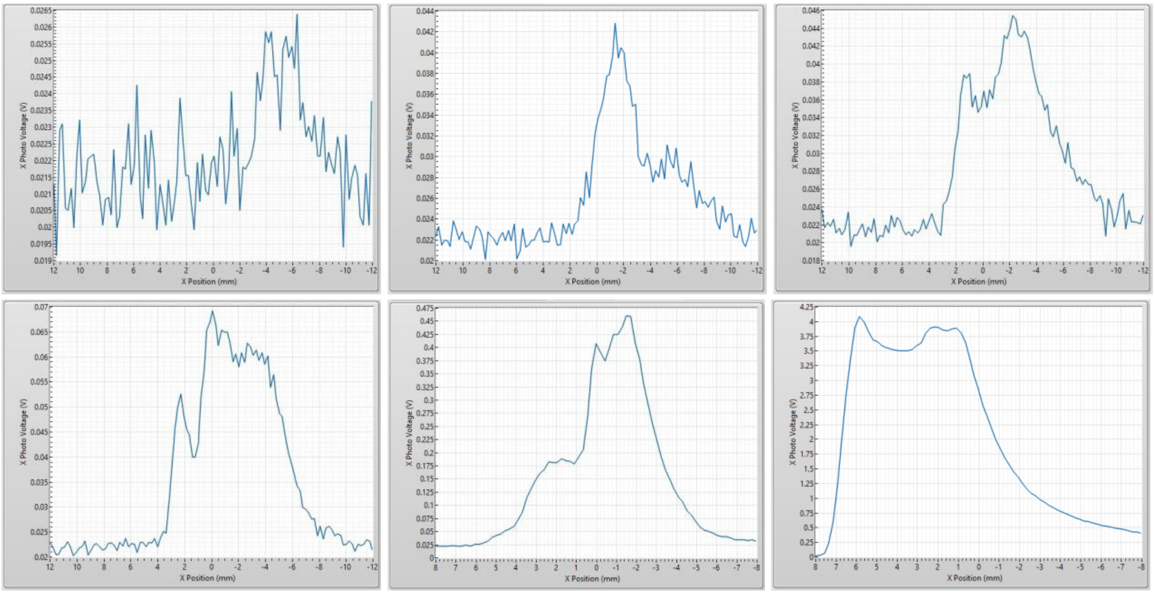

Fig. 7. Beam profiles measured using D-Pace's commercial UniBEaM with 200µ Ce^{3+} fiber, on AEC-LHEP's IBA Cyclone cyclotron. 18MeV H^+ currents 12pA, 62pA, 100pA, 225pA, 1nA, and 400nA

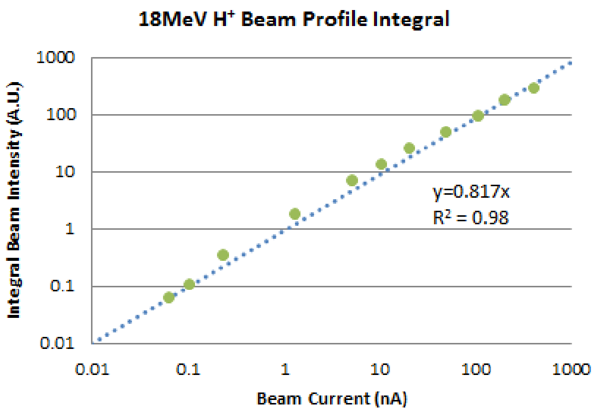

Fig. 8. Integral of beam intensity profile vs beam current measured by Faraday cup

The UniBEaM system commercialized by D-Pace achieved a SNR of 2 at 12pA, and 15 at 100pA, for 18MeV H^+, using the significantly lower cost photo-current-sensing architecture shown in Fig. 3. Using this 18MeV beam as an example, customers operating with beam currents exceeding 100pA could use this cost-effective design, while customers with beam currents less than 100pA could use the higher-performance, higher-cost photon-counting approach use by AEC-LHEP.

D-Pace also used the commercial UniBEaM system to tune the beamline of our TRIUMF-licensed DC volume-cusp H^- ion source. Fig. 9 shows the effects of beam steering on the position of a 25keV 500µA proton beam. For these measurements, a non-doped fiber was used, which had sufficient impurities to produce sufficient scintillation for this high current, low energy beam.

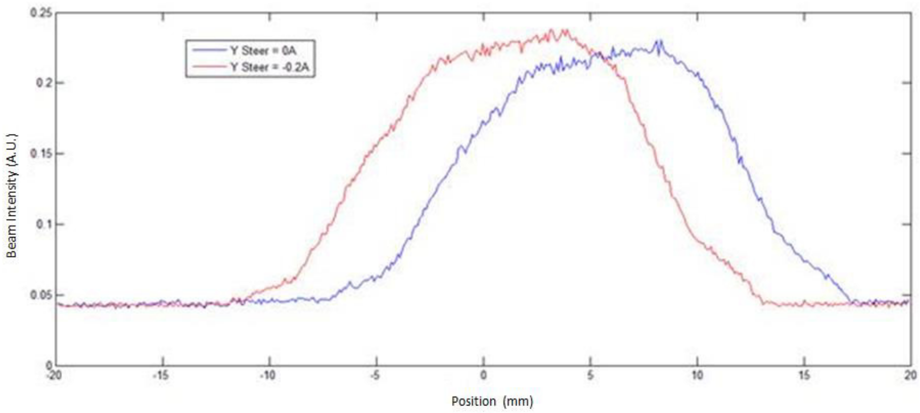

Fig. 9. Beam profiles showing the effects of a beam steering of a 25keV 500µA H^- beam

Mones et al. (2006) at the University of Milano-Bicocca's Department of Materials Science studied the use of rare-earth doped fibers for dosimetry, measuring radio luminescence emitted from a Clinac 2100 CD (Varian, USA) medical linear accelerator, with both photons and electrons. Their prototype had satisfactory reproducibility and good linearity over the dose range of interest (from few cGy to approximately 10 Gy). D-Pace also made preliminary measurements of the scintillation of Ce^{3+} doped SiO_2 fibers with X-ray (6MeV, 15MeV) and electron (6MeV, 12MeV, 20MeV) beams emitted from a Varian Model iX5 medical linear accelerator. These results will be discussed in future publications.

5. **Future Work**

Nesteruk et al. (2015), at the AEC-LHEP, demonstrated the use of UniBEaM for measuring the transverse emittance of their IBA Cyclone cyclotron using two different methods – quadrupole variation and multiple UniBEaM probes. D-Pace plans to develop software for using UniBEaM for transverse emittance calculations.

D-Pace is designing 50mm beam diameter (64mm beam pipe) and 75mm beam diameter (100mm beam pipe) versions of UniBEaM – all of which will have the same insertion length as the 25mm beam diameter (38mm beam pipe) probe described in this paper. A UHV version of UniBEaM is in progress.

D-Pace is investigating the manufacturability of scintillation fibers with diameters of 50µm and smaller for the purpose of scanning beams with diameters less than 1000µm.

D-Pace is working with industrial and scientific partners to explore applications for UniBEaM. D-Pace has an early adopter program where UniBEaM systems are offered at discounted rates in exchange for data sharing and product feedback.

6. Conclusions

UniBEaM is an alternative to conventional wire scanners, and offers the particle accelerator industry a compact and cost effective means of measuring charged particle, electron and x-ray beam intensity profiles over a large range of currents and beam energies.

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